Don't Forget the Loudspeaker —
A History of Hemispherical Speakers at Princeton, Plus a DIY Guide

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Abstract

This paper gives a historical overview of the development of alternative sonic display systems at Princeton University; in particular, the design, construction, and use in live performance of a series of spherical and hemispherical speaker systems. We also provide a DIY guide to constructing the latest series of loudspeakers that we are currently using in our research and music making.

Keywords: loudspeakers, hemispherical speakers, sonic display systems, laptop orchestras.

1. Introduction

In developing new instruments for musical expression, one of our main areas of interest has been the end of the audio chain: the loudspeaker. For several years we have been investigating the use of alternative sonic display systems, resulting in a number of novel spherical and hemispherical speakers.

As we have wrangled with the conventional means of amplification of electronic sounds, particularly in situations in which we have attempted to merge our sonic and musical concerns with acoustic musicians, there have been many serious issues raised. For example, one of the advantages of playing a conventional acoustic instrument is the unspoken ability to work with the dimension of space and location. Imagine a small group of acoustic musicians playing together, such as a string quartet or a jazz combo. As a player in this ensemble, the relationships and interactions with other musicians are based not only on the kinds of sounds that are created, but also on the specificity of the player's location in space with respect to other players, and the implications that physical and present musical being presents to the ensemble as a whole.

In the realm of electronic music, these basic issues become problematic, and have for years given way to a different kind of relationship between electronic and acoustic musicians. For example, consider a typical computer music concert in which an electronic performer's sound absorbs and dominates the sonic space through the stereo sound field of a modern PA system, or further, through a massive surround system of multiple

loudspeakers. In this environment, any acoustic musician involved becomes overwhelmed by the sonic and spatial power of this system, and is forced to submit to an artificially narrow sonic space, or is simply absorbed into the mix by being amplified (or "processed") and thrust into a dislocated sonic field. This can result in some powerful performance paradigms, but the subtleties of ensemble space and location are lost, as well as a true distinction between the acoustic performer and the electronics (not to mention the social implications of such an absorption). This is not to say that spatial concerns are not dealt with; they become a kind of "outside-in" approach, in which sounds are placed in the stereo field, or in the multi-channel surround environment, necessitating a "sweet spot" that, unfortunately, the performers themselves are rarely able to gain access to.

Much of our work over the past few years has been to both *reduce* the sonic power of electronic musicians and to increase the *spatial* abilities of those voices; not only in order to more effectively combine electronic voices with acoustic ones, but to reclaim the powerful ensemble relationships that inherently exist in purely acoustic ensembles. In short, we are interested in reducing the overwhelming dispersion and density of electronic music in exchange for the subtly of chamber and orchestral traditions. So a laptop orchestra is much more than a gathering together of many laptop musicians; it is about finding ways of working with many voices in space and time, and creating an ensemble in which ensemble space and location are reclaimed as important and individual sonic concepts.

The result of such concerns has taken us in many different directions, from using guitar amps for amplification to performing with small, near-field monitors. The problems with these systems, of course, is that they are front-firing systems that do not radiate out in all directions the way acoustic instruments do, thus creating sonic imbalance both within the ensemble and even in the audience (try sitting in the direct line of fire of a guitar amp). Thus, we have developed a series of spherical and hemispherical "inside-out" loudspeakers that attempt to replicate the behavior of acoustic instruments. Through many years of trial and error, and also of observing the excellent work of others, including the Compact Spherical Loudspeaker Array developed at CNMAT in Berkeley [1], and the IRCAM digitally controlled 3D array of loudspeakers [2], we have settled upon a hemispherical design that is lightweight, compact, and compatible with any laptop. This has been an important concern since, in addition to the fact that we

individually gig with our speakers on a regular basis, we also have also been working with large groups of players via the Princeton Laptop Orchestra (PLOrk) [6], which has necessitated a large number of speakers (we can accommodate well over 25 players at this point).

What follows is a short history of our research, design, engineering, and construction, as well as a description of our latest hemispherical speaker design. In addition, we provide instructions for making your own self-amplified hemispherical speaker.

2. The Near Complete History of Princeton Spherical and Hemispherical Speakers

2.1 1997

It all began with Dan Trueman, and his dissatisfaction with using guitar speakers to amplify his electric violin. Perry Cook took this to heart, and paying a visit to Bed Bath & Beyond and Radio Shack, he took up his trusty saber saw and other tools. "The Bomb" resulted (Fig. 1a). Disturbed by the lack of isolation of the individual speaker drivers, Perry paid a visit to many Radio Shacks and a Home Depot. This resulted in "The Boulder" (Fig. 1b).

Being an IKEA type, Dan secured some wooden salad bowls (as opposed to the metal ones used for the Bomb). After some time in the Cook basement speaker lab, the spher-o-nauts had some seriously cracked bowls on their hands. The bowls had to go to Long Island for "glue and clamp rehab" in the wood shop of Dr. Trueman Sr. With some tom-tom mounts and legs, "R2" was born (Fig. 1c).

2.2 1998

Aside from his other talents, Dr. Laurence Trueman (Dan's dad) is one wicked good woodworker. He worked out the angles for his power saw so it could cut hunks of wood such that they assemble into a wonderful sphere with twelve individual enclosures (think "Best of Boulder and Bomb"). Alliterations nearly aside, "The Critter" was created. This was integrated into the Bowed Sensor Speaker Array (BoSSA) (Fig. 1d) [3].

Figure 1. (a) Bomb. (b) Boulder. (c) R2. (d) BoSSA.

2.3 1999

Growing weary of building spheres by hand, Dan and Curtis Bahn found United Speaker Enclosures, who were selling spheres with one driver in them. We convinced them to make us a bunch of spheres and hemispheres with 12 (and 6) speaker mounting holes. "Generation 2" was born (Fig. 2a). Figure 2b shows the DigitalDoo, integrating an ancient instrument with sensors, mics, and a hemispherical speaker.

Meanwhile, Bahn had become infected with the spherical speaker virus, and set out to make a really big one based on the design of "The Critter," for use with his sensor bass. The result: "Bubba" (Fig. 2c) Once he had made the biggest, Curtis wanted to make the smallest too, but to emphasize portability and sensor control of sound and music performance. Out popped the "Bubba Ball," (Fig. 2d) which was not really a spherical speaker, but a controller heavily inspired by one. Soon it was common to see Dan, Curtis, Perry, and others playing together with strange looking spherical and hemispherical speakers in a variety of live performance situations [4][5].

Figure 2. (a) Gen2. (b) DigitalDoo. (c) Bubba. (d) Bubba Ball.

2.4 2001

Stephan Moore, a graduate student working with Curtis Bahn at Rensselaer Polytechnic Institute, worked with his professional cabinet maker uncle, Ken Malz, to create lots and lots of these nice hemis of "Generation 3" (Fig. 3a).

2.5 2005

Dan Trueman, Perry Cook, Ge Wang, and Scott Smallwood started the Princeton Laptop Orchestra (PLOrk) in the fall of 2005 [6][7][8][9]. Meanwhile, Stephan Moore and Ken Malz began designing an improved speaker, with better wood (MDF board) and larger drivers. Cook, Trueman, and Smallwood tacked onto this a multi-channel interface capability. This six-channel "4th Generation Hemi", the Gray Hemi, hit the scene. This hemi was also the first to be produced and sold commercially, and is still being sold by Electrotap (www.electrotap.com). (Fig. 3b).

Figure 3. (a) Generation 3. (b) Generation 4.

2.6 2008 – The Dawning of the Age of Delorean

Although the Gray Hemi design had provided years of success, one of the main obstacles for PLOrk was

portability. Part of our weight and bulk issue had to do with amplification and interfacing. Since we have been using 6-channel hemispherical display systems, we require six channels of amplification per player, thus an external equipment rack populated with not only needed amplifiers (Stewart DA-70-2 and DA-70-4) but also the computer audio interfacing box (Edirol FA-101) as well as sensor/controller interfacing (Electrotap Tea-boxes).

Thanks to recent advances in amplifier technology [10], we began to explore integrating amplification electronics into the speaker enclosure. In addition, as interfacing technology has evolved, particularly in the areas of custom sensor interfacing and the widespread adoption of the USB 2.0 protocol for Human Interface Devices (HIDs), we were able to further eliminate the specialized devices that we had been using previously. The result is that we are now scaled down to two primary pieces of equipment: a laptop, and a hemispherical speaker containing its own amplification, with a small firewire audio interface mounted to the bottom of the speaker. A third optional piece of equipment is a subwoofer, currently a Yamaha YST-FSW050. Figure 4a shows our standard minimal PlorkStation for spring 2008. Figure 4b shows the newest "Delorean" speaker design. Figure 4c shows a TeQWire Nano singer laptop/music stand with dual hemispherical speakers which are also self-amplified.

Figure 4. (a) PlorkStation '08. (b) Delorean . (c) TeQWire Nano.

3. Build Your Own Delorean

The Delorean hemispherical speaker (figure 4b) is a self-amplified, six-channel loudspeaker in an aluminum hemispherical case. It features a six-gang volume pot that controls the overall volume of all six drivers. The speaker requires a 4 Amp 12-Volt DC power source, and features a single 6-pin XLR jack to input six line-level signals into the amps (requiring a special adapter). The design is also equipped to accommodate the mounting of a multiple-channel USB interface underneath the speaker. Here is a guide to constructing a Delorean and adapter cables.

3.1 Ingredients

Two of the components for this project include custom designs: the Charlize[1] Amplifiers and the 6-gang

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potentiometers[2]. All other parts are generally available from many electronics supply companies; obviously you can substitute your own favorite speakers, knobs, etc.[3]

3.2 Building the Speaker

3.2.1 Step 1: Building the Aluminum Shell

Building this speaker first involves creating the shell. There are many different ways to build a speaker shell. The one we describe here involves cutting sheets of aluminum and welding them together, so it may not be for the faint of heart. However, if suitable metal-shop skills and equipment are available, these instructions will get you there. Ours were laid out and built by Lawrence McIntyre in the Princeton University School of Engineering and Applied Science Machine Shop (Figures 5-7).

1a.) Cut out main body, cut large holes in all panels and half holes in half panels. Drill and tap 8/32 holes in all panels excluding the half panels for speaker mounts.

1b.) Bend up all panels 110 degrees. Weld at half panel joint. Sand joint smooth.

1c.) Cut out, drill and tap bottom plate. Weld to main body. Sanding is not necessary on the bottom plate.

1d.) Cut out top plate. Cut out large holes and drill and tap 8/32 holes for speaker mounts. Weld to main body. Sand smooth with radius.

1e.) Fabricate jig to drill and tap 8/32 holes in half panels.

1f.) Apply finish

There are obviously other options available for creating shells. Our TeQWire nanos (figure 4c) are built using mixing bowls. The Standford Laptop Orchestra uses hemispheres made from wooden salad bowls. See also the Low Cost Spherical Speaker Array [11].
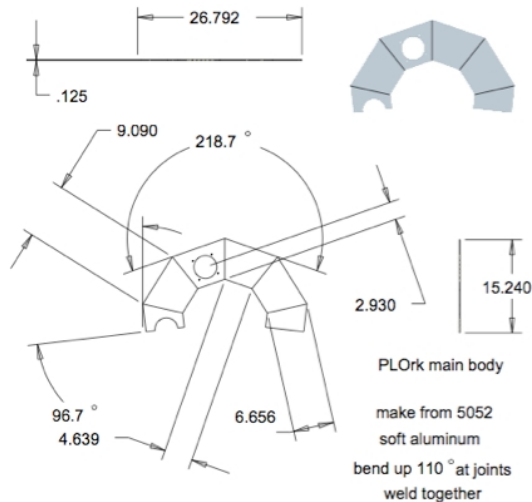
3.2.2 Step 2: The Guts

Once you have built the shell, it's time to build and mount the guts, which includes the amplifiers, jacks, and volume pot, and all of the wiring to connect everything together. Standard 22 AWG stranded hookup wire works fine for all wiring.
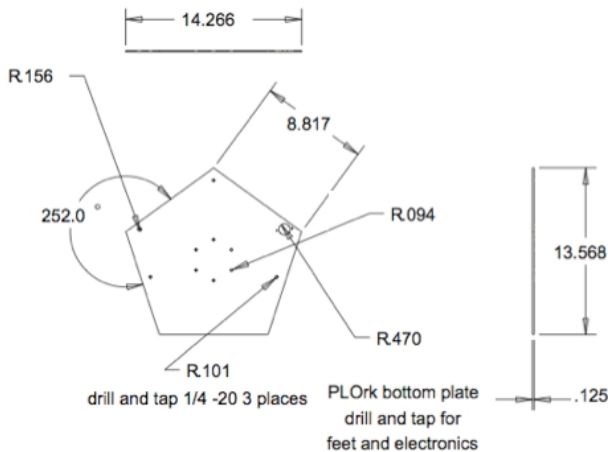
2a.) Solder a common 12-inch ground wire to all the potentiometer grounding terminals. (see figure 8).

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[1] Charlize amp boards are available from DIY Paradise and Calv Acoustic Labs at http://diyparadise.com/charlize.html. Our version includes DC blocking capacitors, which also roll off frequencies below 80 Hz (we use subs for the low end). There are also other manufacturers using the Tripath class-D amps (T-amp). We use the TA2020 at 10-20Watts (8Ω-4Ω) per channel.

[2] The potentiometer was custom built by potentiometers.com according to our specifications: Series 70, conductive plastic, 3/4" shaft with 3/8" bushing and 3/8" shaft protruding. 50K log taper, 6 gang. As of January 2009, the part number is L26190.
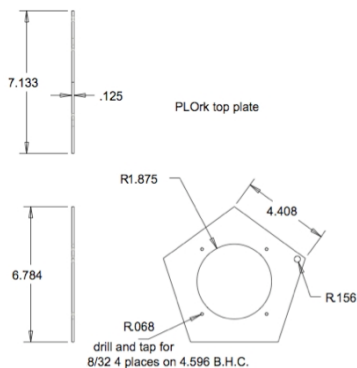[3] For more information about the specific parts we used, including a detailed parts list with prices as of 2009, see http://silvertone.princeton.edu/~skot/plork/delorean/

Figure 5. Main body of enclosure

26.792
.125
9.090
218.7 °
2.930
15.240
96.7 °
4.639
6.656
PLOrk main body
make from 5052
soft aluminum
bend up 110 °at joints
weld together

Figure 6. Bottom plate of enclosure

14.266
R156
8.817
252.0 °
R.094
13.568
R.470
R.101
drill and tap 1/4 -20 3 places
.125
PLOrk bottom plate
drill and tap for
feet and electronics

Figure 7. Top plate of enclosure

7.133
.125
PLOrk top plate
R1.875
4.408
6.784
R.156
R.068
drill and tap for
8/32 4 places on 4.596 B.H.C.

2b.) Solder six 36-inch long colored wires to each of the pot's lower terminals, and one 36-inch long black wire to the ground. Twist them together into a cable harness.

Figure 8. Input wiring of pot

2c.) Now solder six 8-inch long wires, using the same color scheme as the cable harness above, to the middle, right-most terminal of each pot position. Twist these together into three pairs, as shown:
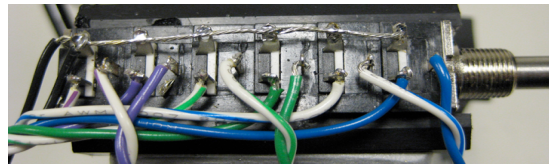

Figure 9. Output wiring of pot

2d.) Solder three pairs of the wires above to three different Charlize boards. Whatever you chose for channels 1 and 2, for example, white-purple/purple, will be soldered to the left and right input terminals of a Charlize board. Do the same for channel pair 3 and 4, and pair 5 and 6.


Figure 10. Input wiring to Charlize boards

2e.) Using red and black wire, solder the power terminals of each Charlize board together and connect them to the coax jack; and include the ground common ground wire of the pot in this power ground.
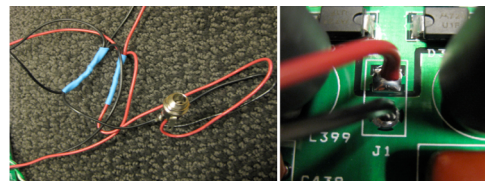
Figure 11. Power wiring

2f.) On each Charlize, solder an 8-inch pair of wires to the left and right output terminals of the board. Use the same color scheme to identify channels. For example, the white-purple/purple input wires of channels 1 and 2 match white-purple/black for left out, and purple/black for right out.

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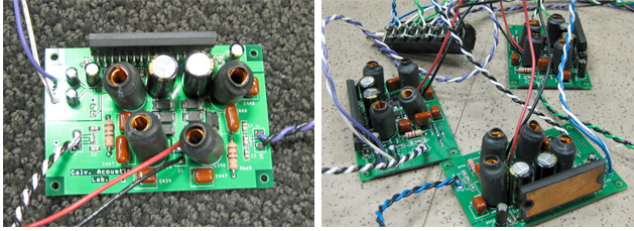
Figure 12 (a) Charlize board with all leads. (b) all three.

An important final step before mounting the guts inside the shell is to TEST each amp channel to make sure it works. Plug the amps into a 12V power supply and run test leads to each input on the pot from a line audio source (CD, iPod, etc.) and connect a speaker temporarily to the corresponding output. If all works, go on to the next stage.

3.2.3 Step 3: Install the Guts

This is a delicate and often frustrating operation that involves mounting the amps and all of their appendages into the center of the shell. Here it is very important to make sure the shell has the proper holes drilled.

3a.) Mount short pieces of foam on each end of the back of the Charlize boards. Then use nylon cable ties to fasten the three Charlize boards together into the shape of a triangle. Don't connect the final side yet.
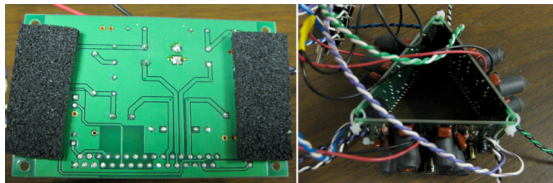
**Figure 13. (a) Charlize foam mounting (b) 3-board cluster**

3b.) Stuff the boards into the shell through one of the speaker holes, and fasten the final side together to finish the triangle. Position it in the center. Mount the volume pot on top and the power jack on the bottom in their predrilled holes.


Figure 14. Potentiometer installation

3d.) Paint the bottom of each of the TRIAD amp chip with thermal adhesive. Then position the board cluster in the center of the inside of the hemi so that the six circular holes on the bottom will line up with the half-moon indentations on the TRIAD amp chip of each board, as shown. Use 6-32 machine screws and nuts, and be careful not to over-tighten! Use threadlocker on the screws and

nuts. NOTE: Orient the three amps towards the speaker holes whose speakers they will power, if possible.
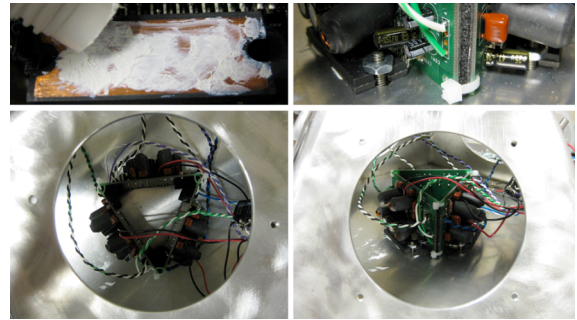
Figure 15. Mounting cluster inside speaker enclosure

3e.) Thread the long cable harness from the volume pot through the jack mounting hole. Solder the leads to pins 1-6 for channels 1-6, and solder the ground lead to the jack grounding terminal. Mount the jack using 4-40 machine screws. Remember to use threadlocker! NOTE: Make sure that the tab on the jack faces the right edge of the speaker.
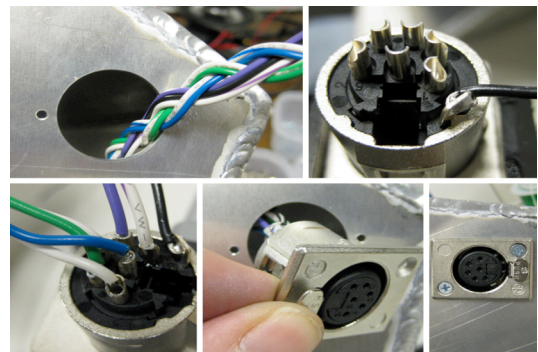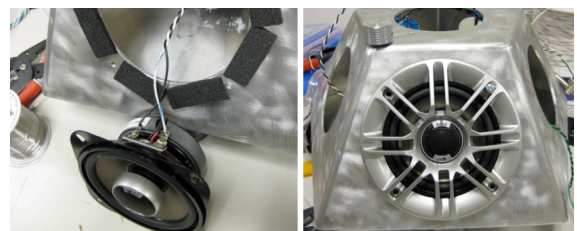

Figure 16. Audio input jack installation

3.2.4 Step 4: Install the Speakers

4a.) Mount some foam around the openings for the speakers, enough so that any flat metal or plastic part of the speaker flange will not rattle.

4b.) Pull out the appropriate pair of leads for each speaker, solder, and carefully mount the speaker. Use threadlocker!

Figure 17. Solder, foam, and mount the speakers

4c.) Before installing the sixth and last speaker (top), first fill the inside of the speaker with acoustic fiber. Put in a lot of fiber—but don't over-stuff. Make sure that wiring and boards are not pressed-upon too much.

3.2.5 Testing

Once the speakers are all in place, mounted, and ready to go, it's time to test your speaker. This can be done in many ways, and should involve testing each speaker independently and together with the others.
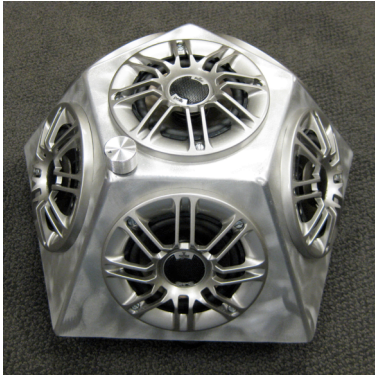

Figure 18. Completed Delorean.

3.3 Connecting Cable/Adapters

The audio inputs for the six channels are accomplished via a six-pin XLR jack. You can build your own adapter, or you can order them custom from HAVE, Inc (they will create custom cables for a fee – and they have made many of these for us). The adapter we use features an XLR male plug on one end, and six RCA male plugs on the other.

Figure 22a shows a six channel cable (we use this to connect to a U46 USB interface, which is mounted under the speaker). The tip from each RCA (or 1/4") plug should be connected to one of the 6 pins on the XLR connector. The shield/grounds of all phone plugs are tied together and connected to the ground flange on the XLR connector. Be sure that the right angle is oriented properly (pins should be along the bottom as jack faces down and towards you). The mono version (Figure 22b) features one input that is split out six ways. The tip of the phone jack should be connected to ALL pins (1-6). The shield/ground of the phone jack should be connected to the ground flange on the XLR connector.
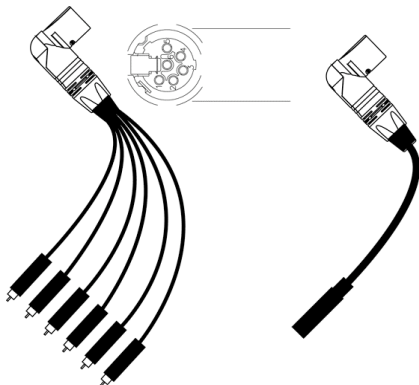

Figure 19. (a) Multi-adapter. (b) Mono-adapter

4. Evaluation and Future Work

In the performance of electronic music, the question of amplification is, of course, an inherent concern. The ultimate choices that are made about amplification have an obvious effect upon the resulting music. Our use of personal hemispherical speakers has proven to be "life changing," dramatically altering the way we compose, improvise, and perform. It's an amazing to be able to walk in to a room, unpack, plug in, and start playing music with others without the usual concerns about speakers, mixers, and the rest of it. It's all right there. The change of sonic focus from a room-enclosing mass to a personal resonator has proven to be a fascinating place to work. This is not to say that we have created a "better" or more effective situation; rather, it simply illustrates that we have found ourselves in a new place, which is always exciting. We hope to continue to find new ways of making sound with this powerful resource, including some future outdoor, zero-carbon performances via batteries and solar power.

Acknowledgements

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